
BROADBAND OPTICAL RECTENNA FOR ENERGY HARVESTING

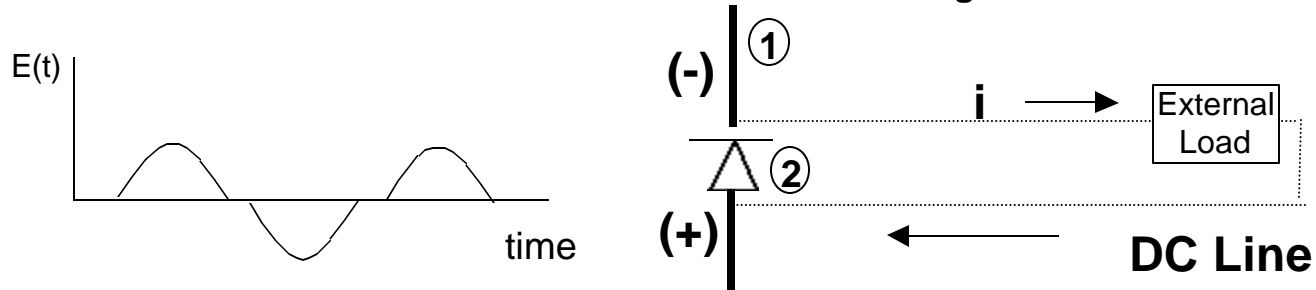
CECOM ENERGY HARVESTING PROGRAM

April 14, 2000



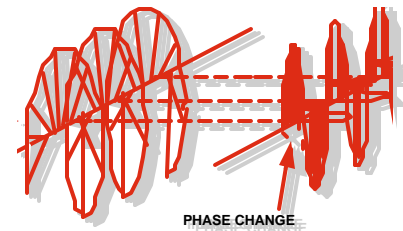
PRINCIPLES OF OPERATION-REVIEW

- 1) Incoming radiation is coupled through an antenna element (engineered to guide surface plasmon waves (skin effect) at higher frequencies) to create a modulated AC electric field
- 2) Direct current harvested across a matched MIM tunneling diode barrier



Characteristics (Solar radiation)

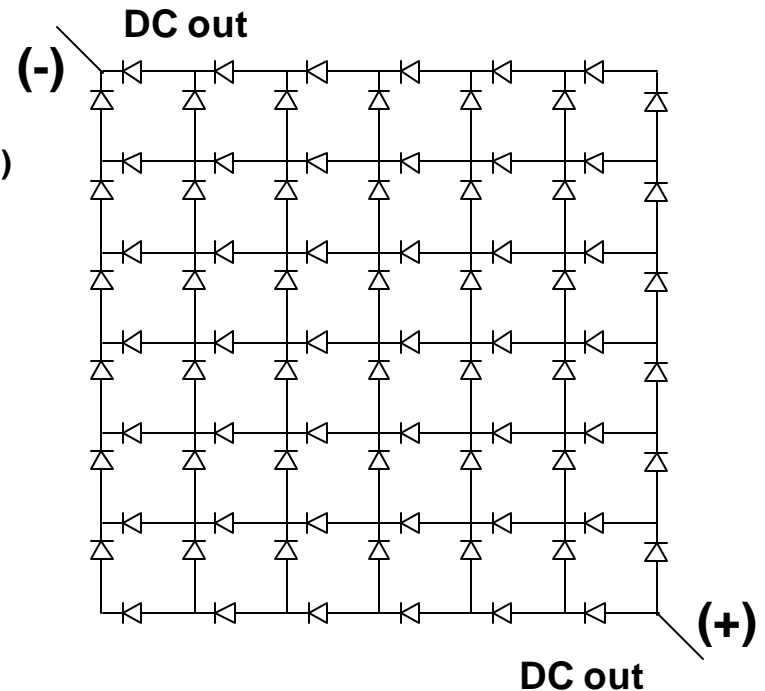
- Average radiation power/unit area equal to 1500 W/m^2
- Over 95% of spectrum contained in $2 \text{ }\mu\text{m}$ (150 THz) to $0.3 \text{ }\mu\text{m}$ (1000 THz) band; 4:1 Bandwidth
- Time Harmonic components are not polarized and therefore considered as elliptically polarized



COUPLING- INCOMING SOLAR RADIATION

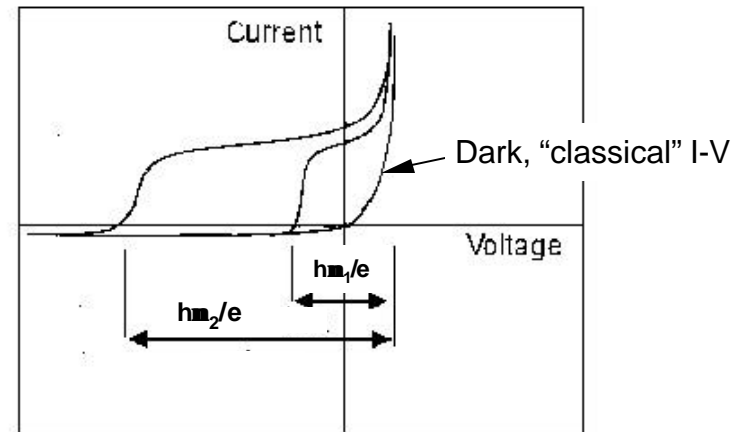
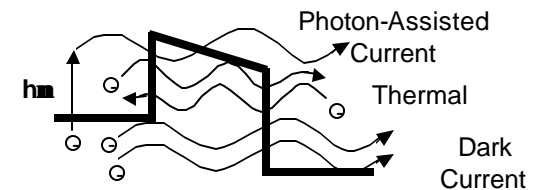
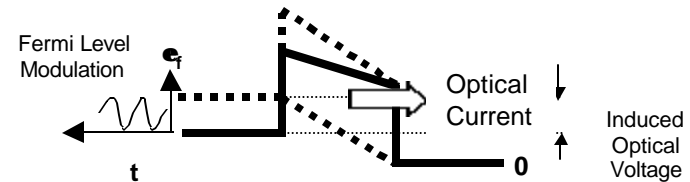
- **Design Strategy**

- Antenna (Rectification) scales with frequency enabling low frequency performance (i.e., efficiency) validation
- Broadband (4:1) grid array (with loaded grids $< 0.5 \lambda$) is ideally suited due to the symmetry of horizontally and vertically polarized waves
- Since polarization of the sun is statistical, two feeds for each orthogonal polarization
- Prior art: low frequency, “rectenna” concepts demonstrated $>85\%$ efficient (full wave rectify)
- Capitalize on frequency independent characteristics of diode



RECTIFICATION: FREQUENCY DEPENDENCE

- **Above THz:**
 - I-V characteristics show additional peaks due to field-assisted electron tunneling processes
 - Increased power output within an integral number of photon energies, $h\nu/e$, of the diode turn-on voltage
- **Below THz:**
 - Response rolls over to classical rectification ($h\nu/e$ is smaller than the voltage scale of the DC non-linearity)



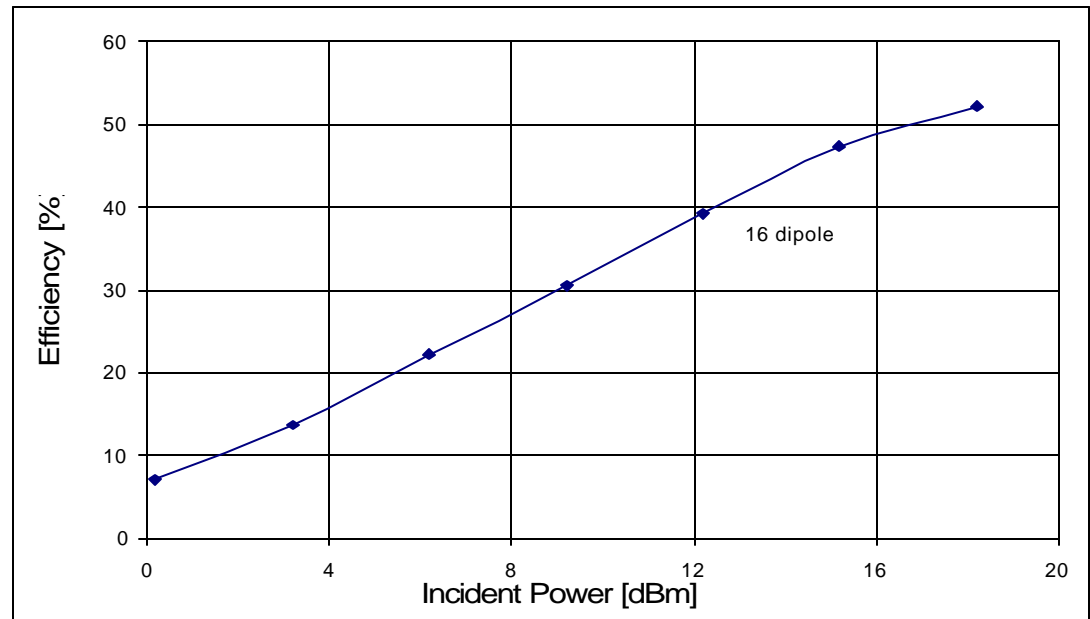
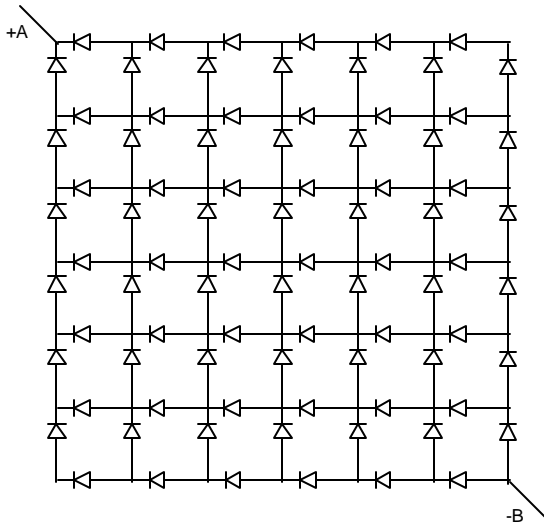
SOLAR ENERGY HARVESTING - FOM

- **GOALS:** Exceed theoretical limit (i.e. 30%) of single junction solar cells in solar spectrum
 - **Quantum efficiency:** i.e. $\frac{\text{\# of electrons by which current changes}}{\text{\# of incident photons}} > 90\%$
 - **Conversion efficiency:** > 40% in THz region (i.e quantum regime)
 - **Power density:** > 30 mW/cm² (> 30 mW out from incoming 100 mW/cm²)
- **APPROACH:** Due to inherent frequency scaling attributes, validate concept and performance at low frequency; transition to high (quantum) frequencies.
 - **Barrier Engineering** in tunneling diode at both low (micron scale) and high (nano scale) frequency
 - **Monolithic, parallel processing** provides geometric scaling



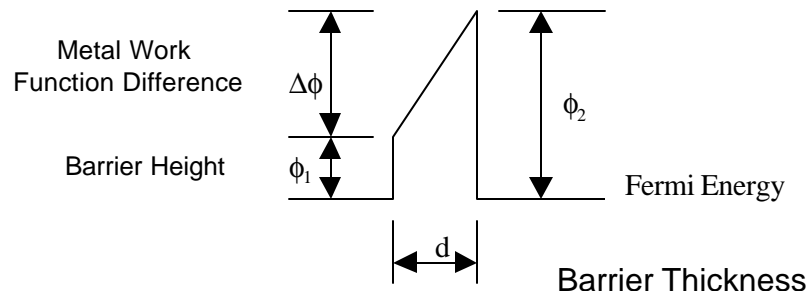
LOW FREQUENCY (10 GHz) DEMONSTRATION

- Measured efficiency @ 10 GHz with inexpensive Schottky diodes (4:1 bandwidth)
- Efficiency limited only by saturation of diodes
- Both 30 GHz and monolithically integrated 90 GHz demos in progress (w/ MIM diodes)



PARAMETRIC STUDY OF MIM TUNNEL DIODES

- Assumes trapezoidal barrier from BDR Model

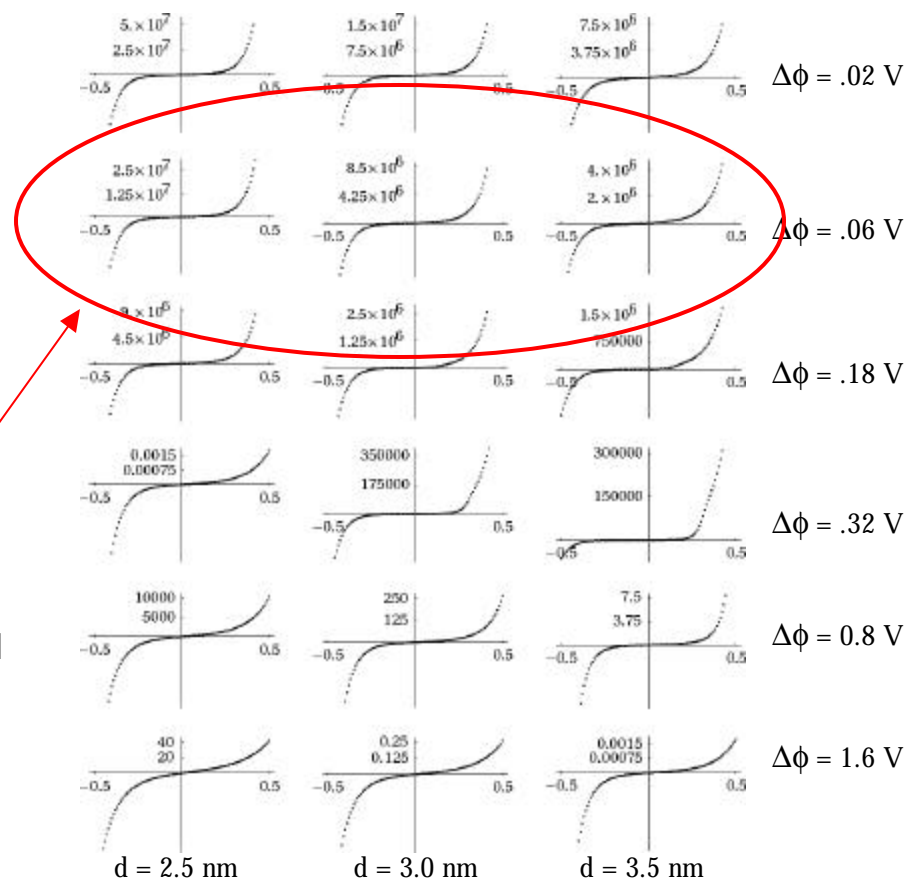


- Barrier Parameter Space

- Heights: 0.02 \rightarrow 0.2 V
- Thickness: 2.5 \rightarrow 3.5 nm
- Current test system: Nb/NbOx/Ag

- Balance between quantum efficiency (93%) and coupling efficiency (antenna matching)

- Engineer non-linearity and asymmetry (conversion efficiency non-optimized)

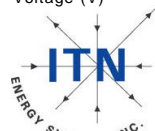
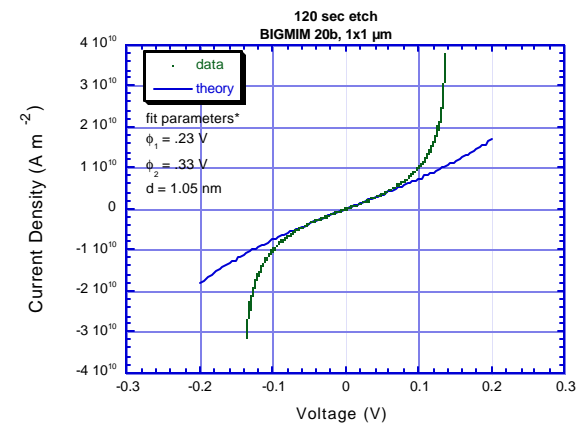
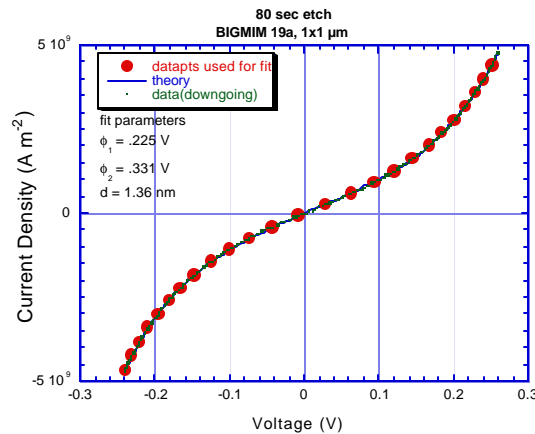
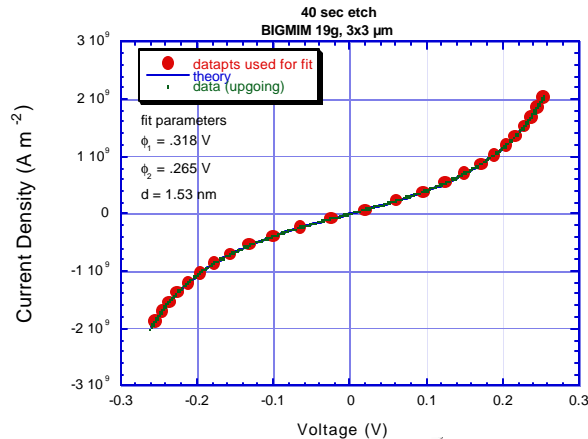
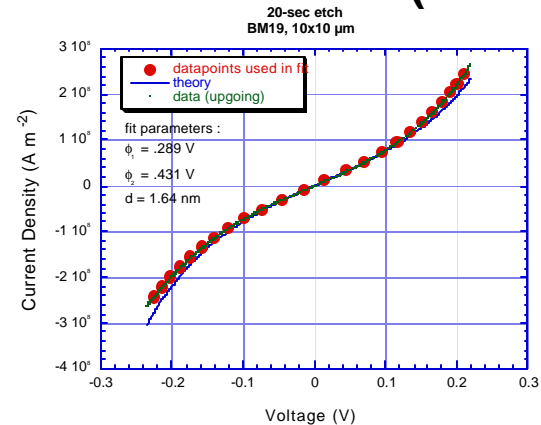
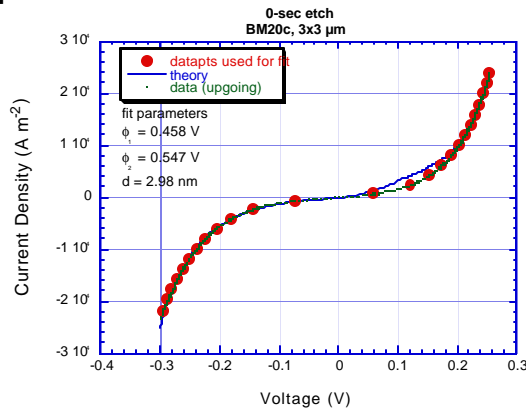


$$\Phi_1 = 0.36 \text{ V}$$



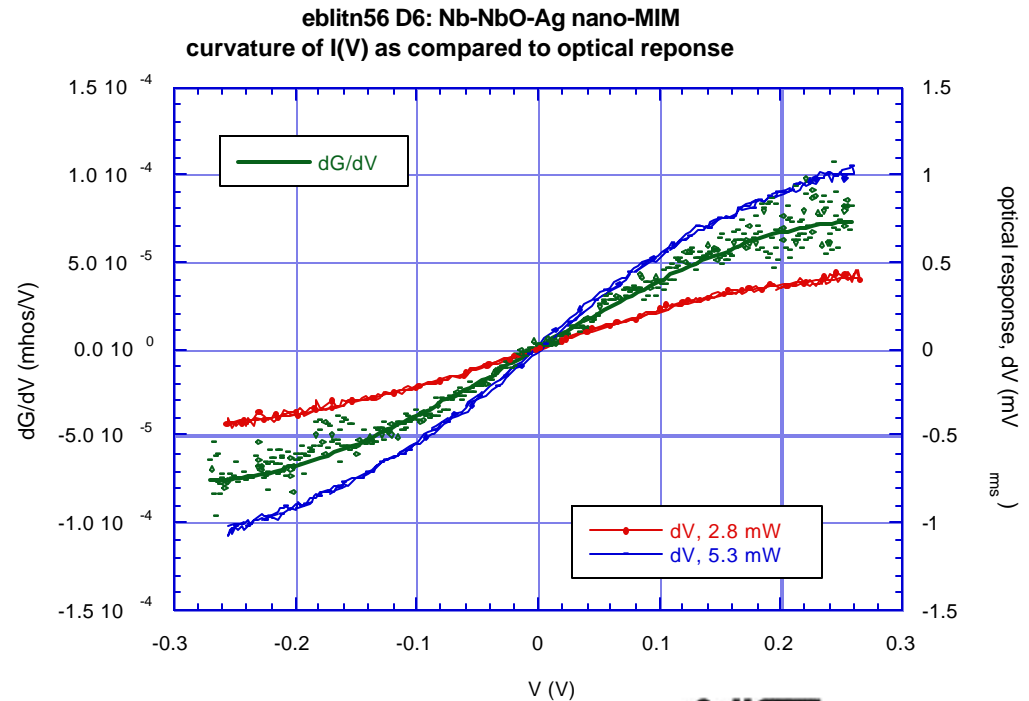
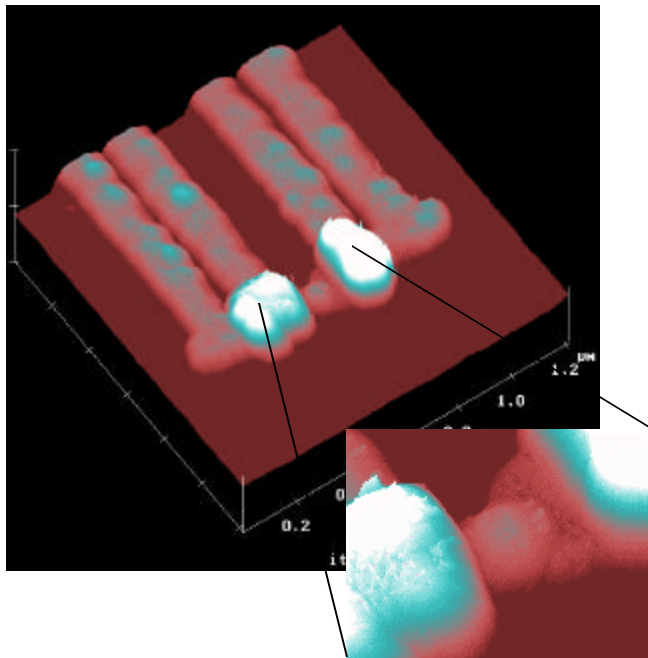
BARRIER ENGINEERING-MODEL VALIDATION

- I-V response as a function of decreasing barrier thickness (nanoscale MIM)




OPTICAL RECTIFICATION @ 30 THz

- Observed optical rectification with a R.T., unbiased planar MIM diode
- Demonstrated high current capacity (tested to 500 mW) and process yield



SUMMARY-UNIQUE FEATURES

- **Energy Coupling**
 - Planar, broadband (4:1) grid array structure to couple to incoming elliptically polarized (complex) wave (engineerable coupling)
 - Efficiency limited only by saturation of diode (Schottky)
- **Rectification AC**  (both classical and quantum)
 - Vacuum deposited, planar (lithographic) MIM diode structure with minimal parasitic capacitance loss
 - Ability to optimize, via engineering of non-linearity/asymmetry, classical responsivity; first ever zero bias optical response @ 30 THz for planar MIM
 - Ability to balance high quantum efficiency and impedance matching to achieve high conversion efficiency (current challenge)
- **Design**
 - Frequency scaling: performance optimization at low frequency, large size and then scale to high frequency
 - Geometric scaling: Large area, parallel processing (i.e., soft lithography/self organizing arrays) with monolithic integration



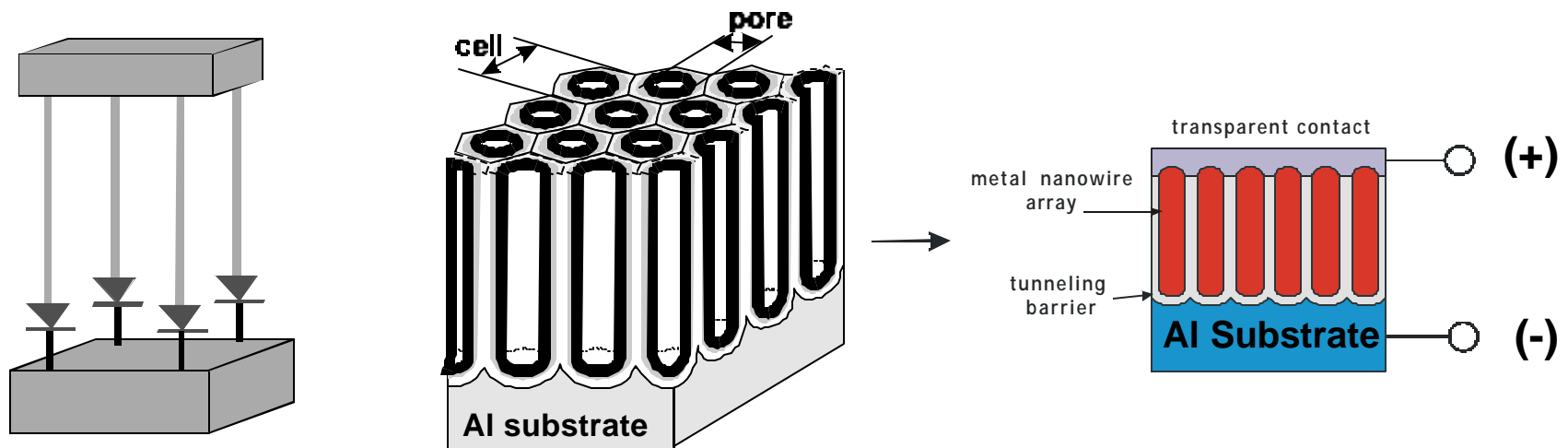
Applications - Energy Harvesting

- **Optical Frequencies (long term payoff)**
 - Direct power integration into microsystems, such as micro-sensors, micro-electromechanical, and micro-air vehicles
 - In combination with rechargeable battery, high efficiency power source for portable and remote electronics
- **Millimeter/Microwave Frequencies (near term payoff)**
 - Recycling (DC power generation)/shielding of stray RF fields at antenna tower stations (also cellular base stations)
 - **Stealth** (broadband absorption of reflected, complex polarized source?)
 - **“Spin-off”**:
 - » Passive millimeter ranging @ 90 GHz (concept in progress)
 - » Active metal detection (security) @ 90 GHz



Applications - Energy Harvesting (cont)

- Infrared Frequencies
 - Harvest IR radiation from blackbody sources at off-normal incidence
 - Use (3-D) monopole array to couple with near/far field of source (i.e., TPV emitter or low temperature source such as fuel, wood, etc.)
 - Feasibility demonstration using low-cost, electrochemical processing techniques



Applications - Other

- **Imaging/Sensing/Detection**
 - **Performance attributes**
 - » **Extremely high bandwidth (30 THz) => high speed device (optic); as compared to 3-5 THz for high speed Schottky diode (SOA)**
 - » **High non-linearity => high quantum efficiency (93%)**
 - » **Un-cooled operation (i.e., room temperature IR detection)**
 - **Fabrication**
 - » **Low-cost, parallel processing**
 - » **Monolithic integration (incorporate sensor with downstream electronics)**
- **Integration of multiple functions into single platform**
(i.e., antenna, energy harvesting, detection, etc.)

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